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## Development of a swimming motion display system for athlete swimmers' training using a wristwatch-style acceleration and gyroscopic sensor device

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### Abstract

The objective of this study was to develop a swimming motion display system for athlete swimmers' training, which is handier and more intuitive than the three dimensional motion capture systems using underwater cameras. In this paper, system structure, reconstruction method of the swimming motion, experiment on land to examine the accuracy, and the software which reconstructs and displays the swimming motion are described.

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### 1. Introduction

In the recent training of competitive swimming, it is important to check and analyze carefully the swimming motion of the swimmer. In order to know the underwater swimming motion, filming by the underwater camera has been basically necessary. In the present training, filming by one underwater camera is often carried out. However, filming only by one underwater camera cannot provide sufficient information for the three dimensional swimming motion. Therefore, in the training of the first-class athlete swimmers, three-dimensional motion capturing with filming by two (or more) underwater cameras is sometimes conducted. Although the three-dimensional motion capture system can provide sufficient information, it is known to be expensive and troublesome to set up cameras and to perform the post measurement process, such as digitizing images. Therefore, it is difficult to use such systems in daily training.

The authors have developed a wearable data logger which is attached to the swimmer's wrist and has sensors to measure swimming stroke. It has already been shown that various evaluations of the swimming stroke, such as stroke technique, is possible using the data obtained from the logger [1][2][3]. When wearable sensors are employed

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to measure the swimming motion, expensive motion capturing equipment is not necessary, and the post measurement process becomes much easier than the motion capturing. In addition to these merits, it may be possible, by the wearable sensors, to measure slight differences of the stroke which are difficult to distinguish from the images. These merits are thought to be appropriate for the daily training.

The authors, on the other hand, have recently developed the swimming human simulation model “SWUM” (SWimming hUMAN Model) [4][5]. The analyses of the four strokes [6][7] and the development of the free software “Swumsuit” were carried out [8]. Using this simulation technology, it is possible to compute the fluid force acting on each part of the swimmer, as well as to visualize them by animation.

The objective of this study was to develop a swimming motion display system for athlete swimmers’ training by integrating the above-mentioned authors’ technologies, which is handier and more intuitive than the three dimensional motion capture systems using underwater cameras. The developed system consists of a sensing unit and software. The sensing unit, which is attached to the swimmer’s wrist, measures and records the tri-axis acceleration and angular velocity of the swimming stroke during training. The software reconstructs the swimming motion from the measured results which are transmitted from the sensing unit, and displays estimated fluid forces acting on the swimmer’s hand and forearm. In this paper, system structure, reconstruction method of the swimming motion, experiment on land to examine the accuracy, and the software which reconstructs and displays the swimming motion are described.

## 2. System structure

The system structure is schematically shown in Fig 1(a). In this system, a wristwatch-style sensing unit is attached to the swimmer’s wrist. The photograph of the sensing unit is shown in Fig 1(b) and (c). The sensing unit consists of the main chip (which includes a microcomputer, wireless module, and three accelerometers (H48D) for three axes), three gyroscopic sensors (XV-3500CB) for three axes, and battery. The whole is cased in a waterproofed housing. One reason why the motion at the wrist is measured is that main thrust in the three swimming strokes except the breaststroke is known to be produced by the upper limbs. Another reason is that the motion of the hand and forearm can be approximately measured by measuring the wrist motion since the range of motion of wrist in swimming is known to be smaller than those of other joints.

The data measured by the sensing unit is wirelessly transmitted to a PC on land after the training. The transmitted data are visually presented to the athletes and coaches through the software as explained in Section 5.

## 3. Reconstruction method of swimming motion from the signals detected by sensors

The reconstruction method of swimming motion (defined as direction and locus of hand and forearm) from the acceleration and angular velocity obtained from the sensing unit at the wrist is explained in this section. First, three coordinate systems are defined: the absolute coordinate system  $O\text{-}XYZ$ , a moving coordinate system  $o_i\text{-}x_i\ y_i\ z_i$  which is fixed to the sensing unit at time step  $i$ , and a reference coordinate system  $o_1\text{-}x_1\ y_1\ z_1$  which is  $o_i\text{-}x_i\ y_i\ z_i$  at the first time step of one stroke cycle. The unit vectors of the moving coordinate system at the time step  $i$  in the reference coordinate system are denoted by  $N_i = [N_{xi}\ N_{yi}\ N_{zi}]$ . That is, the unit vector of the reference coordinate system at the time step 1 is written by

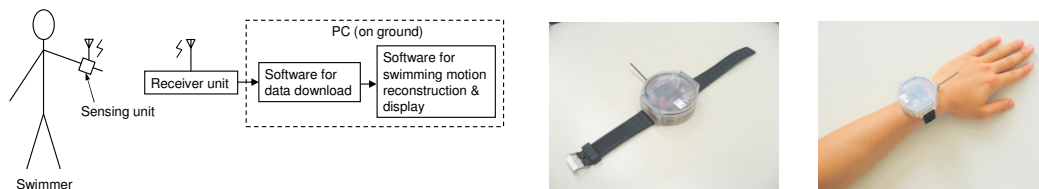


Fig. 1. (a) schematic figure of system structure; (b) wristwatch-style sensing unit; (c) wearing view of the sensing unit

$$N_{x1} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, N_{y1} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, N_{z1} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (1)$$

The transformation matrix  $T_i$  to represent the moving coordinate system at a time step  $i+1$  in that at time step  $i$  is written by

$$T_i = \begin{pmatrix} 1 & -\theta_{zi} & \theta_{yi} \\ \theta_{zi} & 1 & -\theta_{xi} \\ -\theta_{yi} & \theta_{xi} & 1 \end{pmatrix} \quad (2)$$

In this equation, the rotation angles for three axes ( $\theta_{xi}$   $\theta_{yi}$   $\theta_{zi}$ ), which are calculated by multiplying the angular velocity  $\omega = (\omega_{xi} \ \omega_{yi} \ \omega_{zi})$  and time step  $dt$  together, are regarded as sufficiently small. Using  $T_i$ , the set of unit vectors  $N_2$  is represented by

$$N_2 = T_1 N_1 \quad (3)$$

In order to obtain  $N_3$ , the angular velocity at the previous time step  $\omega$  is employed. In order to employ it, it is necessary to transform the angular velocity in the moving coordinate system  $\omega$  into that in the reference coordinate system  $\omega'_2$  as

$$\omega'_2 = \omega T_2 \quad (4)$$

The transformation matrix  $T_2$  can be derived using the rotation angles ( $\theta'_{x2}$   $\theta'_{y2}$   $\theta'_{z2}$ ) which are the products of  $\omega'_2$  and the time step  $dt$ , and  $N_3$  is derived as

$$N_3 = T_2 N_2 \quad (5)$$

By repeating the above procedure for the number of time steps, the unit vectors of the moving coordinate system  $N_i = [N_{xi} \ N_{yi} \ N_{zi}]$  in the reference coordinate system at time step  $i$  can be obtained. Using this  $N_i$ , the acceleration in the moving coordinate system  $A_i$  also can be transformed into the acceleration in the reference coordinate system  $A'_i$  as

$$A'_i = N_i A_i \quad (6)$$

The translational acceleration is obtained by subtracting the gravitational acceleration from the above acceleration, since the acceleration measured by the accelerometer includes gravitational one. The velocity and position can be obtained by integrating this acceleration using the trapezoidal rule.

The following part in this section describes the correction method of the error which occurs in deriving the direction and locus from the angular velocity and acceleration measured by the sensing unit. In general, experimental values measured by the accelerometers and gyroscopic sensors include the errors due to various causes. Therefore, if these measured accelerations and angular velocities are employed for the time integration, errors accumulate successively and finally it becomes considerably large at the end. In this study, therefore, it is assumed that the direction and position (relative to the swimmer) are always the same at the moment of start of the stroke cycles since the swimming motion is basically cyclic. Based on this assumption, the direction is corrected as follows: Denoting the time step at the end of a cycle by  $n$ ,  $N_n$  is written by

$$N_n = T_z T_y T_x N_1 \quad (7)$$

where  $T_x$ ,  $T_y$ ,  $T_z$  represent the rotation matrices for the three axes. Denoting the rotation angles by  $\psi$ ,  $\theta$  and  $\phi$  respectively, the rotation matrices are written by

$$T_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\cos\psi \\ 0 & \cos\psi & 1 \end{pmatrix}, \quad T_y = \begin{pmatrix} 1 & 0 & \cos\theta \\ 0 & 1 & 0 \\ -\cos\theta & 0 & 1 \end{pmatrix}, \quad T_z = \begin{pmatrix} 1 & -\cos\phi & 0 \\ \cos\phi & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (8)$$

Solving the angles  $\psi$ ,  $\theta$  and  $\phi$  from Eq.(7), the discrepancy between the coordinates at the first and end of the cycle can be obtained. In this study, this discrepancy (error) is assumed to increase linearly. Based on the assumption, the rotation matrices for each time step  $i$  can be written by

$$T_{xi} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\cos(\psi/(n-1) \cdot (i-1)) \\ 0 & \cos(\psi/(n-1) \cdot (i-1)) & 1 \end{pmatrix}, \quad T_{yi} = \begin{pmatrix} 1 & 0 & \cos(\theta/(n-1) \cdot (i-1)) \\ 0 & 1 & 0 \\ -\cos(\theta/(n-1) \cdot (i-1)) & 0 & 1 \end{pmatrix},$$

$$T_{zi} = \begin{pmatrix} 1 & -\cos(\phi/(n-1) \cdot (i-1)) & 0 \\ \cos(\phi/(n-1) \cdot (i-1)) & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (9)$$

Multiplying the unit vectors at each time step  $N_i$  by the inverse matrices of Eq.(9), the direction after the error correction at the time step  $i$  can be written by

$$N'_i = T_{xi}^{-1} T_{yi}^{-1} T_{zi}^{-1} N_i \quad (10)$$

In addition to this correction, consider the case when the initial direction in the absolute coordinate is tilted from that of Eq.(1) and this direction is denoted by  $N_0$ . The unit vectors of the moving coordinates in the absolute system are obtained by the following transformation

$$N''_i = N_0 N'_i \quad (11)$$

Using this direction in the absolute coordinates, the acceleration in the absolute coordinates finally can be written by

$$A'_i = N''_i A_i \quad (12)$$

By time integration of this acceleration and deducting the gravitational acceleration, the velocity in the absolute coordinates is obtained. In this time integration, the velocity is corrected using the same algorithm as above, based on the assumption that the terminal velocity should be equal to the initial one. The position is also obtained by the similar procedure.

#### 4. Experiment on land to examine accuracy of the developed system

In order to examine the accuracy of the developed system including the above-mentioned reconstruction method, an experiment on land was carried out. In the experiment, one subject was asked to perform the imitated swimming motion on land, and the results of motion measurement were compared to those by three dimensional motion capture system. The sampling frequency of the sensing unit was 190Hz. As the motion captures system, MAC3D (Motion Analysis Corporation) was employed. Seven markers were attached to the subject: one for shoulder, two for elbow, two for wrist, and two for hand. The imitated motions of the breast and crawl strokes were performed. An example of output from the sensing unit for the imitated breaststroke is shown in Fig 2. In this trial, the sensing unit was mounted to the left wrist. The subject performed the stroke motion for one cycle from the initial state in which the upper limbs were stretched straight forward such as the gliding position, and restored the upper limbs into the same state as the initial one after the stroke. Two peaks for two times at the start and end in Fig 2 were due to tapping the sensing unit in order to make the recognition of the start and end easier. It was confirmed that the results represent the characteristics of the stroke motion. The reconstructed loci of the breast and crawl strokes are shown in Fig 3. In Fig 3(a), the top view is shown and negative direction in X is forward. It can be seen that the left wrist starts from the origin, draws a lunate shape counterclockwise, and returns to the initial position. In Fig 3(b), the side view of the

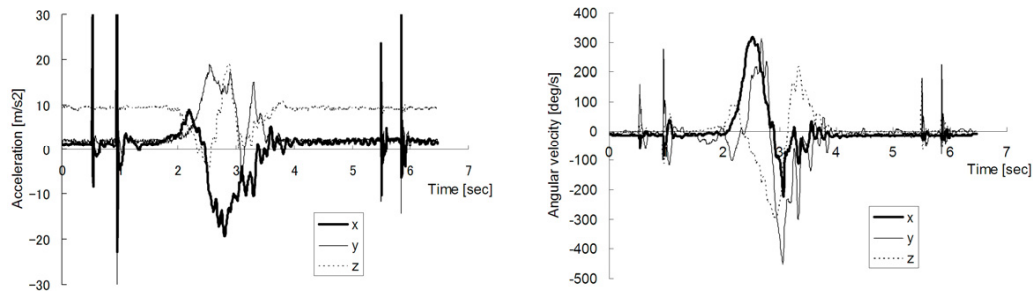


Fig. 2. measurement results by the sensing unit (imitated breaststroke) (a) acceleration; (b) angular velocity

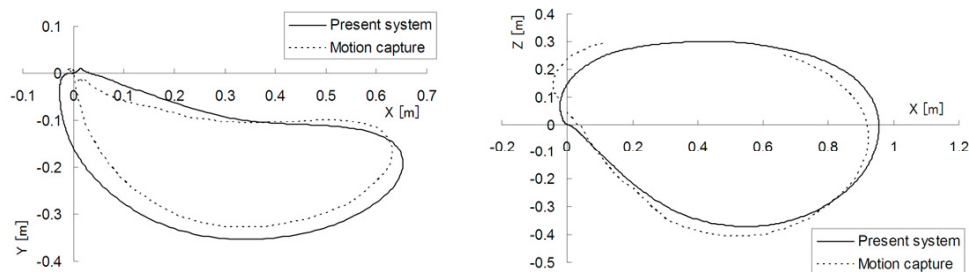


Fig. 3. results of motion reconstruction (a) breaststroke (top view); (b) crawl stroke (side view)

crawl stroke is shown, negative direction in  $X$  is forward, and positive  $Z$  is upward. The locus starts from the origin and a distorted circle is drawn counterclockwise. The reason why the curve by the motion capture system (dotted line) was partly broken was that the markers could not be distinguished around the moment. From Fig 3, it was found that the results by the present system represented the features of the swimming motions well, although it has errors of 50mm in the maximum compared to the motion capture system. In addition to this error, in the reconstructing process of Fig 3, the initial direction of the sensing unit was determined so that the reconstructed locus agree with that by the motion capture system as well as possible. Therefore, it will be an important task for the system in the future to solve the problem of how to acquire the initial direction, as well as the improvement of the accuracy.

## 5. Software which reconstructs and displays swimming motion

In order to display visually the reconstructed swimming motion to the athletes and coaches, a software with a graphical user interface was developed. In this software, the user first clips one stroke cycle of the swimming motion data watching the screen. Then, by clicking “Analysis start” button, the swimming motion is reconstructed and the animation of hand and forearm of the swimmer is displayed. Examples of the screenshots are shown in Fig 4. In Fig 4(a), the fluid forces acting on the hand and forearm are calculated and displayed using the function coordinated with the simulation model SWUM. The directions and magnitudes of the fluid forces are represented by the lines emitting from the hand and forearm. Although this function has been implemented by invoking “Swumsuit”, which is an implementation of SWUM, it can be used for the user only by clicking the “Create files for fluid force” button, without any knowledge about SWUM and Swumsuit. The software displays not only the fluid force acting on each part of the body, but also the averaged value of the total thrust for one stroke cycle.

Two swimming motions are superimposed in one screen in Fig 4(b). As shown in this figure, multiple swimming motions can be displayed simultaneously by the present system. This function can be applied in the various training

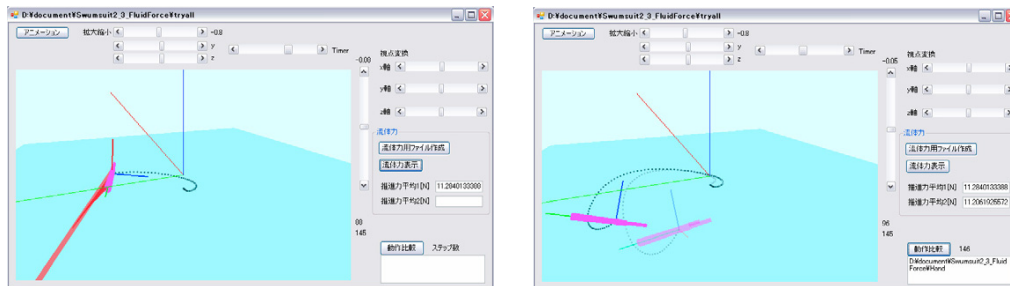


Fig. 4. screenshots of the developed software (a) displaying fluid force acting on forearm and hand; (b) displaying two swimming motions for comparison

scenes, such as comparing the swimming motion in a bad condition with that in a good one, and comparing the motion at the start of training in a day with that at the end in a tired condition. In addition to these, it also becomes possible, by employing the coordinated function with SWUM, to obtain easily the quantitative information which has not been obtained in the training to date, such as the difference of the averaged values of the thrust in one stroke cycle for the two compared motions.

## 6. Conclusions

In this study, a swimming motion display system for athlete swimmers' training, which consists of a wristwatch-style sensing unit and software for reconstructing and displaying the swimming motion, was developed. Although the qualitative validity of the system was shown in this paper, a lot of tasks are to be done for the present system, such as acquiring the initial direction, improvement of the accuracy, and more user-friendly interface. The authors would like to solve these tasks and improve this system in the future studies.

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